

PREScribed FIRE IN THE MANAGEMENT OF *MELALEUCA QUINQUENERVIA* IN SUBTROPICAL FLORIDA

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ABSTRACT

Melaleuca (*Melaleuca quinquenervia*) is one of the most invasive nonnative tree species in South Florida. Its adaptations to fire include a thick bark, epicormic sprouting, and serotinous seed capsules. Fire can facilitate the spread of *melaleuca* by triggering seed release, but fire exclusion is not a practical long-term option for managing infested South Florida natural areas. We sought to find life history stages or times of year during which *melaleuca* is susceptible to fire in order to incorporate prescribed burning into an integrated control program, one that includes herbicide treatments and, perhaps in the future, biological control. Specifically, we looked at the potential for prescribed fire to kill seedlings established after seed release triggered by chemical treatments. Field studies showed that most seedlings <50 cm tall are killed by prescribed fire. The results of this research have been successfully incorporated into the large-scale control program at Big Cypress National Preserve and elsewhere in the region. Rather than excluding fire, fire is used as a follow-up treatment to herbicide application to destroy released *melaleuca* seeds and seedlings.

keywords: control, germination, *melaleuca*, *Melaleuca quinquenervia*, mortality, prescribed fire, seed rain, seedlings, South Florida, wetland.

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INTRODUCTION

The on-going, multi-billion dollar restoration of South Florida will do little to protect natural areas if the threat of invasive exotic species is not successfully challenged. One of the most serious exotic threats is *melaleuca*, an Australian tree. *Melaleuca* is a fire-adapted plant that is capable of colonizing many of South Florida's fire-maintained habitats. Burning favors the spread of *melaleuca* by causing the release of vast numbers of stored seeds and rarely results in the death of mature trees.

Melaleuca invades marshes, wet prairies, cypress swamps, and pinelands, all common habitats in the southern end of the Florida peninsula that require fire for continued survival (Wade et al. 1980). Fires can occur at any time of year in South Florida, but the largest area burns during May, at the end of the annual dry season. The smallest area burns during September and October, at the end of the rainy season, when wetland areas are flooded to the greatest depths (Snyder 1991).

Melaleuca is a slender, upright tree averaging 12–20 m in height at maturity that can tolerate periodic flooding and fire. Its fire tolerance is in part due to a thick, shaggy bark that insulates the living tissue of the bole while at the same time serving as a medium to carry fire into the canopy. Smaller, less insulated branches are killed, but these are readily replaced from epicormic buds on the main stem and larger branches.

The tree resprouts below any point on the bole not killed by fire. In some cases, seedlings less than 1 year old may sprout at the root collar (Myers 1984).

Flowers are borne on the current season's growth with additional branch growth continuing beyond the flowers. The inflorescence produces a cluster of 30–40 serotinous capsules, each containing approximately 250 seeds (Myers 1983). The capsules will open only after a break occurs in their vascular connection with the branch (Meskimen 1962). Although fire is the primary agent responsible for this break, freezing temperatures, herbicides, radial growth of the branches, and natural pruning due to shading elicit the same response. *Melaleuca* seeds are minute and unwinged (approximately 34,000 seeds/gram). A single open-grown tree can carry >20 million seeds (Laroche 1994).

During the early 1900s, *melaleuca* was introduced simultaneously on the east and west coasts of southern Florida. During 1943, John Henry Davis, in his classic monograph of the natural features of southern Florida (Davis 1943), did not mention *melaleuca* as a feature in the landscape. Since that time, the spread of *melaleuca* has been phenomenal. Today it dominates the vegetation in much of western Lee County and in the East Everglades region of Miami-Dade and Broward counties. There are severe infestations in Loxahatchee National Wildlife Refuge, water conservation areas in the South Florida Water Management District, and, formerly, in Big Cypress National Preserve. *Melaleuca*

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also has significant populations in Palm Beach, Collier, and Charlotte counties. Any significant northerly advance appears to be limited by freezing winter temperatures, so the more northerly infestations generally occur in coastal counties. By 1993, melaleuca was estimated to dominate about 200,000 ha of southern Florida (Laroche 1994).

The first steps formally addressing the melaleuca problem in Florida were undertaken by the Florida Game and Fresh Water Fish Commission (now the Florida Fish and Wildlife Conservation Commission), which organized and conducted several melaleuca workshops during the late 1970s. The lead taken by the Game and Fresh Water Fish Commission stimulated action and interest among other agencies at the local, state, and federal levels, and spurred creation during 1984 of the Exotic Pest Plant Council. The council serves as a forum for airing views, sharing available data, and discussing management and control problems of alien pest plant species in addition to melaleuca.

At the time this research was initiated, during the late 1980s, the situation concerning melaleuca was regarded as rather bleak (Hofstetter 1991, Myers 1991). Agencies participating with the Exotic Pest Plant Council had demonstrated that melaleuca could be controlled by the expensive and time-consuming process of treating individual trees with herbicides. The herbicide treatments were complicated, however, by the need to re-treat a significant number of trees that resprouted and, more importantly, by the fact that the death of the melaleuca crown stimulated the release of massive amounts of seed. Control efforts in some cases may have actually contributed to the spread of this species.

Because fire triggers the seed release that results in the spread of melaleuca, managers avoided the use of prescribed burning and attempted to exclude fire from habitats with mature trees. This is not a viable long-term solution, however. While there may be no further spread of melaleuca in the absence of fire, undesired successional changes occur in the vegetation. Furthermore, even with active fire suppression, there will inevitably be a wildfire that will burn the area and potentially result in massive regeneration.

Although melaleuca is superbly adapted to fire, we wanted to investigate if there were vulnerable points in the life cycle where prescribed fire could be used to its detriment. It was known, for example, that some seedlings could be killed by fire. We conducted a series of studies supported by the Florida Game and Fresh Water Fish Commission and the National Park Service during a 4-year period in Big Cypress National Preserve, a 295,000-ha natural area on the northwest border of Everglades National Park. These studies focused on the role of fire in melaleuca seedling establishment and seedling mortality. Additional field studies testing the effectiveness of various herbicides and methods and seasons of application were conducted at the same time. However, one of the herbicides proved to be so effective (Arsenal, now widely used in treating melaleuca) that the use of prescribed fire as a pre-treatment

to make trees more susceptible to chemical treatment became a moot point. Therefore none of the herbicide-related studies are reported here, but are available in a final report (R.L. Myers and H.A. Belles. 1995. Studies to develop melaleuca control tactics using fire and herbicides. Final report to Florida Game and Fresh Water Fish Commission grant #NG87-035 and National Park Service agreement CA 5000-7-8009 No. 2.).

We carried out a series of field studies to address the following: (1) Are germination and survival of seedlings greater on burned sites compared to similar unburned sites? (2) How many and for how long are seeds released after a fire? (3) Under what conditions (or times of year) are seeds released after fire most likely to germinate and then survive the annual cycle of flooding and drought? (4) Can prescribed fire be effective in killing melaleuca seedlings and saplings? (5) Can seedling size, age, or both be used as indicators of when seedlings are capable of resprouting? Based on the results of these studies we made recommendations for the use of prescribed fire in melaleuca control.

METHODS

To compare seedling germination and survival in burned and unburned areas, 5 0.1-m² plots were randomly located within each of 3 prescribed burns and in adjoining unburned areas. The first burn, on 25 October 1990, was at Monroe Station, a site characterized by a grass-dominated wet prairie with scattered dwarf cypress (*Taxodium*) and moderate fuel loads. The second burn, near Oasis Ranger Station, was in a wet prairie site near the edge of a cypress dome with low fuel loads. This burn was conducted on 9 November 1990. The third site, at Monument Lake, had the heaviest fuel loads of wet prairie grasses, scattered cypress, and wax myrtle (*Myrica cerifera*) and was burned 12 March 1991. Approximately 8,000 melaleuca seeds were sown on each of the plots shortly after the sites were burned as follows: Monroe Station, 18 days after the burn, soil saturated; Oasis Ranger Station, 11 days after the burn, soil moist; and Monument Lake, 30 days after the burn, soil very dry. Plots were monitored for seedling establishment and survival for 63 weeks.

Seed rain studies were conducted 18 km southeast of Monroe Station on the south side of Loop Road. On 15 April 1988, an extremely intense wildfire (Charlie Jumper Fire) burned through a melaleuca-infested area containing reproductively mature trees. The fire consumed most of the crowns but left the trees standing. Seed rain was followed within the following 3 habitats at the Loop Road site: (1) Sparse melaleuca. Scattered melaleuca (1.7 individuals/m²) in a wet prairie dominated by muhly grass (*Muhlenbergia filipes*), scattered slash pine, pond cypress, and cabbage palm. Soil is very shallow marl with exposed caprock. Seasonally flooded from June to October with a maximum water depth of only a few centimeters. (2) Dense melaleuca. A monospecific stand of melaleuca (26.7 in-

Table 1. Description of experimental fires at Monument Lake study site.

Date	Ambient temperature (°C)	Relative humidity (%)	Wind speed (km/hr)	Keetch-Byram drought index	Fire behavior
15 Mar 1989	31	36–43	3–6	650	Heading and flanking fire, intense
09 Jul 1989	33	53	3–11	0	Slow-moving head fire over water, very mild
17 Jan 1990	27–28	42	10–13	414	Heading and backing, moderate intensity
17 Mar 1991	24–27	36–41	5–14	610	Head fire, light fuels, mild (reburn)

dividuals/m²) with wet season water levels of 2–10 cm. (3) Cypress dome. A pond cypress dome containing a few large melaleuca trees and surrounded by a monospecific stand of large melaleuca (0.08 individuals/m²). Soil a deep organic muck, seasonally flooded with a maximum depth of 30 cm.

Seven days after the burn, 15 rectangular aluminum baking trays (17.5 × 12.5 cm) were randomly placed on the ground in each habitat. The trays were coated with a thin film of petroleum jelly to serve as an adherent for the seeds. When the trays were placed in the field, seed rain had already begun, so the initial several days of seed fall were not recorded. Trays were monitored daily for the next 2 weeks and after that they were checked every 2 to 3 days through week 7 post-burn. Seeds were counted in the trays, then the trays were wiped clean and a new film of petroleum jelly was applied. Following week 7, heavy daily rainfall and rising water levels made seed collection difficult and counts inaccurate.

The appearance and survival of seedlings after fire were studied at 2 sites: (1) Loop Road, where we documented the fate of seedlings established in 3 different habitats as a result of the Charlie Jumper wildfire, and (2) Monument Lake, where 4 experimental units were established and 3 blocks were burned by prescription. At the Monument Lake site, an area of about 8 ha east of the lake was divided into 4 roughly equal compartments. The vegetation was predominantly marl-based wet prairie composed of muhly grass and other graminoids. Scattered in the prairie were occasional cypress trees and several small cypress domes. Each compartment had numerous melaleuca seedlings, scattered mature trees, and at least 1 dense melaleuca stand, characteristically with mature trees at the center. None of the compartments had burned for 7 to 10 years. The 3 prescribed burns were carried out on 15 March 1989, 9 July 1989, and 17 January 1990 (Table 1). The March and July sites were reburned on 17 March 1991. The Monument Lake site was also used to monitor flowering and seed replenishment by mature trees after fire.

At the Loop Road site, a 0.1-m² plot was established next to each of the seed collection trays. An attempt was made to count seedlings on each plot once per week until the plots became flooded, but this was not always possible. When the plots became flooded, monitoring was suspended until water levels receded and the seedlings were visible again. After the flood waters receded, data were collected less frequently than once per week. Water depth was recorded at each plot during each monitoring period that standing water

was present. Five additional 0.1-m² plots were established in each habitat type to monitor germination by counting and removing the seedlings that appeared each week.

At the Monument Lake site, 80 0.1-m² seedling plots were established on each of the 3 burn compartments. On the March 1989 burn compartment, 4 seedling plots were randomly placed along compass lines radiating from 20 mature, seed-bearing trees. On the other 2 burns, 8 plots were placed near each of 10 mature trees. As with the Loop Road site, the plots were monitored for seedling establishment post-burn and seedling survival through periods of standing water and drought. The same 80 plots were used to monitor germination after the reburn that took place during March 1991.

To document how quickly trees replenish their seed stocks after burning, 3 mature seed trees (diameters at breast height of 19, 22, and 27 cm) that had suffered 100% crown scorch during the March 1989 burn were harvested prior to the reburn. The seed capsule clusters were counted and assigned to 1 of 3 categories: (1) burned and opened after the first fire, (2) mature capsules with viable seed produced since the fire, and (3) immature.

Fire-induced mortality of seedlings and saplings was studied at the Monument Lake site. In each of the 4 compartments, 250 melaleuca seedlings and saplings were equally divided into 5 height classes: 5–20 cm, 21–50 cm, 51–100 cm, 101–200 cm, and 201–300 cm. Only single-stemmed individuals lacking seed capsules were selected and marked with a numbered aluminum tag. Heights (±1 cm) and basal diameters (±1 mm) were recorded for each individual. Burn conditions are shown in Table 1. Survival and growth of individuals on each of the 4 compartments were monitored for 2 years.

The March and July 1989 burns were reburned on 17 March 1991. In the March 1989 compartment, prior to the second burn during March 1991, we tagged 400 seedlings that became established after the first burn. Thus, these individuals were of known age. They were divided into 4 height classes of 100 individuals each: <5 cm, 5–20 cm, 21–50 cm, and 51–100 cm. No seedlings that resulted from the March 1989 burn were >100 cm tall. They were monitored for 1 year after the reburn.

The study was complicated by freezing temperatures during the nights of 25–27 February and 24–25 December 1989 that affected tagged individuals prior to the burns. New individuals were selected to replace

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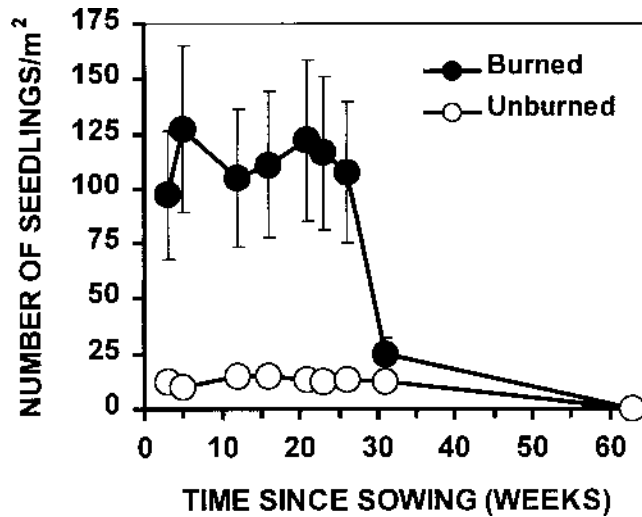


Fig. 1. Numbers of melaleuca seedlings present on burned and unburned prairie at Oasis Ranger Station study site. Mean \pm standard deviation.

dead plants, or plants that were top-killed and no longer fit their intended size-class.

To test the relationship between size and age of seedlings and their ability to recover after topkilling, we grew seedlings in black tree liner pots in a shade-house under 30% "weathershade" cloth. Half of the liners were filled with commercial potting soil and the other half were filled with locally collected pineland sand. We initially assumed that the potting soil would provide a medium more conducive to melaleuca establishment and growth while the pineland sand would represent poorer soil conditions. On 9 July 1990, a pinch of randomly gathered and mixed melaleuca seed was placed in each pot. Establishment turned out to be adequate in the pineland soil, but was very poor in the potting soil. The experimental setup was repeated on 14 August, completely reseeding the pots containing potting soil and reseeding only the pineland soil pots that did not have any seedlings. Thus, we decided to use 3 sets of seedlings rather than 2: (1) pineland soil seeded 9 July, (2) pineland soil seeded 14 August, and (3) potting soil seeded 14 August. Once establishment was assured, plants were thinned to 1 per pot.

During the wet season, daily rains were the main water source. This was supplemented when necessary with tap water filtered with an Instapure water filter. Contrary to our expectations, seedlings in the potting soil exhibited poor growth and appeared chlorotic. To stimulate growth, seedlings in the potting soil were periodically fertilized with 50% strength Peter's All-Purpose Plant Food (6-6-6).

Randomly chosen seedlings were cut to a height of 10 cm to simulate crown consumption, the cut end was then burned until charred, and the base of the stem was burned on 3 sides for 3 seconds each with a hand-held propane torch. Maximum temperatures at the base of the plants were estimated to range from 302–343 °C using temperature-sensitive Tempil pellets.

Because the seedlings in the pineland soil were larger than those in the potting soil, we began treat-

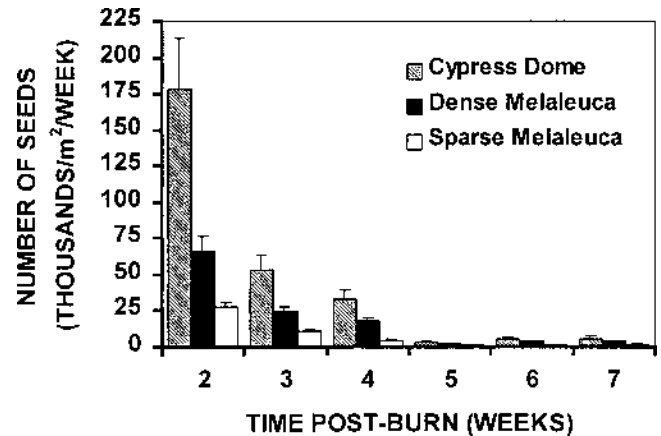


Fig. 2. Seed rain during weeks 2 through 7 after April wildfire in stands of varying density and composition at Loop Road study site. Mean \pm standard error.

ments with them during October 1990 when they were between 2 and 3 months old. Each month for the first 3 months, treatments were applied to a different set of 30 individuals. After the first 3 months, treatments were applied every other month until July 1991. Treatment of the seedlings in the potting soil was not started until they were 5 months old. They were treated at monthly intervals from January until July 1991. Heights (± 0.5 cm) and basal diameters (± 1 mm) were measured the day of treatment. All treated individuals were monitored for resprouting at monthly intervals.

RESULTS

Seedlings appeared within 3 to 4 weeks on the Monroe Station and Oasis Ranger Station (Figure 1) sites that were wet when the seeds were sown, and the number of seedlings peaked within a week or 2 after they began to appear. Germination was delayed for 10 weeks on the Monument Lake site that was dry at the time of sowing. At all 3 sites, observed germination was considerably greater on burned plots than unburned plots. At their peak, the mean number of seedlings present on burned plots exceeded those on unburned plots by a factor of 9 at Oasis Ranger Station, 3 at Monroe Station, and 4.6 at Monument Lake.

At all 3 sites, few individuals advanced beyond the seedling stage. At the Oasis Ranger Station site there was heavy dry-season mortality of seedlings in the burned area. All the remaining seedlings in both treatments died sometime during the subsequent period of extended flooding (Figure 1). At Monroe Station, none of the seedlings in either treatment survived the first dry season. At Monument Lake, where seedlings became established after early wet season rains, most seedlings died during the flooded period. At the end of the monitoring period, only 4 seedlings remained dispersed among 3 of the 5 burned plots.

Figure 2 shows the melaleuca seed rain that fell on the 3 habitat types following the Loop Road wildfire. Seed fall during the first week post-burn, although

Table 2. Germination of melaleuca seeds following a severe wildfire on 15 April 1988. Seedlings were removed from 0.1-m² plots in 3 habitats after each monitoring period.

Habitat condition	Days post-fire	Mean number of seedlings/0.1 m ²		
		Sparse melaleuca	Dense melaleuca	Cypress dome
Dry	27	0	47.2	370.2
	33	0	13.2	241.2
	41	0.2	32.0	267.0
	47	4.2	15.0	453.2
	59	58.6	46.6	38.8
	66	22.2	12.8	3.0
	77	8.0	3.0	28.6
	108	9.4	4.4	18.2
	427	0	0	0
Flooded	232	0.6	0	0
	305	0	0	0
	368	0	0	0
	427	0	0	0

not recorded, appeared quite high because at the beginning of week 2, seeds already carpeted the ground in some places. During the second week, there were >100,000 seeds falling per m² on the cypress site. Overall, the cypress site had about 2 times the seed rain of the dense melaleuca site, and 4 times that of the sparse site. Even though the amount of seed steadily declined each week, by the end of the fourth week post-burn several thousand seeds per m² were still falling on all 3 sites. Seed rain was still measurable at week 7 when the onset of frequent summer rains made sampling impractical. Light seedfall was observed through September.

The differences in seed rain between the 3 habitats is most likely attributable to the number of large seed-bearing trees present. The cypress habitat had the greatest number of such trees. The dense melaleuca habitat was composed of 2 cohorts: (1) scattered multi-stemmed emergent individuals and (2) extremely dense younger individuals that formed a "dog-hair" stand. The sparse melaleuca consisted primarily of scattered smaller trees and did not contain large multi-stemmed trees.

In all 3 habitats at the Loop Road site, germination started at the onset of the summer rains, about 3 weeks after the wildfire. In each case, the greatest number of seedlings was counted just prior to flooding. The maximum number of seedlings in the cypress dome peaked at week 5 with a mean of 1,609 seedlings/m². This was more than 2 times the maximum present at the other 2 sites, probably reflecting the greater number of seeds that fell in the cypress habitat.

Depth of standing water in the cypress dome was 3 times that of the 2 melaleuca stands, which both occurred on wet prairie sites. Regardless of the differences in water levels, very few seedlings survived the wet season flooding in any of the stands. After a year, the mean number of seedlings on the dense stand and cypress dome plots was 34 and 30, respectively, while in the sparse stand only 4 seedlings/m² survived. The seedlings that did survive 1 year were invariably on hummocks or rises associated with the bases of larger

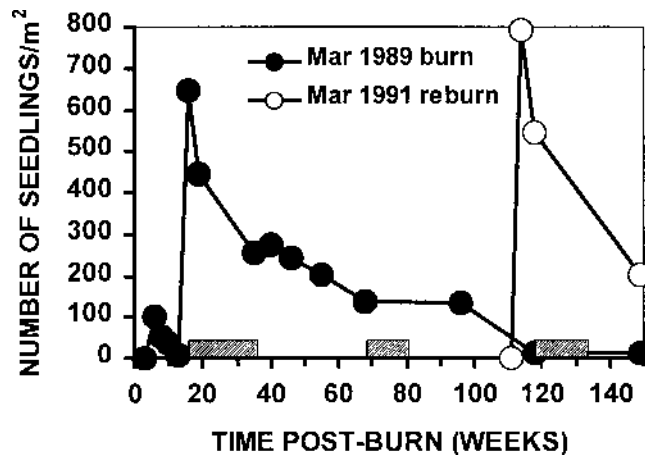


Fig. 3. Seedling establishment and survival following 15 March 1989 prescribed burn at Monument Lake site (solid circles) and after reburn on 17 March 1991 (open circles). Horizontal bars represent periods with standing water.

trees, and thus were flooded for less time than the site as a whole.

Results from the 15 seedling removal plots are given in Table 2. Germination continued from mid-May until early August when the sites became permanently flooded for about 3.5 months. When water levels receded during late November, only 3 new seedlings appeared among all 15 plots, and these were removed on December 3. No additional seedlings appeared on any of the plots after that.

Because the seed-release events took place at 3 different times of year at the Monument Lake site, the results are more indicative of how the timing of burns may favor or limit germination and establishment. Figure 3 shows the fate of seedlings established after the 15 March 1989 prescribed burn. There was an initial pulse of germination following rainfall during April. At week 6 post-burn there was a mean = 103 seedlings/m². These were reduced to a mean = 7 seedlings/m² at the end of a 7-week drought. Another larger pulse of germination occurred at the onset of summer rains during June, when the mean = 645 seedlings/m². There was a steady decline in numbers while the site was inundated during the summer (weeks 16–34 post-burn), with less than half of the individuals remaining at the end of the wet season (mean = 235 seedlings/m²). At the end of the next spring drought these had been reduced to a mean = 139 seedlings/m², most of which survived the next wet season.

The reburn of this compartment reduced the number of survivors to a mean = 12 seedlings/m². In other words, the reburn was able to kill 92% of the surviving individuals established after the first fire. Unfortunately, during the 2-year fire-free interval, the mature trees within the compartment had replenished their stored seed to nearly pre-burn levels. The numbers of burned clusters (i.e., capsules present at the time of the first burn) on the 3 harvested trees were 2,663, 3,971, and 3,689. The numbers of new clusters that were mature at the time of the reburn were 2,402, 1,850, and 1,962. The numbers of immature clusters that would probably

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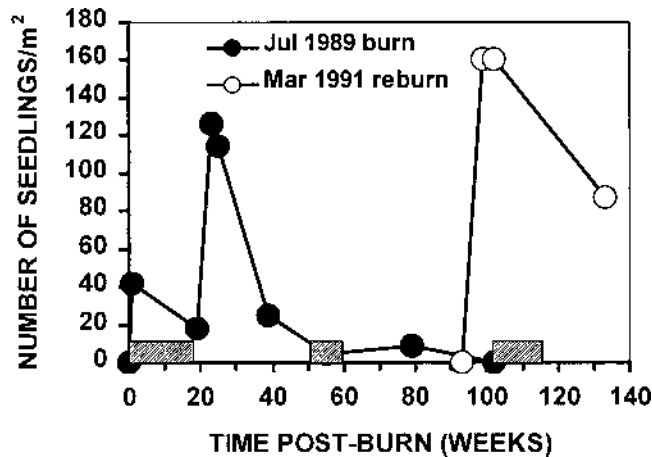


Fig. 4. Seedling establishment and survival following 9 July 1989 prescribed burn at Monument Lake site (solid circles) and after reburn on 17 March 1991 (open circles). Horizontal bars represent periods with standing water.

have matured within a month or 2 were 1,320, 1,521, and 3,905. The second burn resulted in another huge crop (mean = 793 seedlings/m²). Their fate followed essentially the same pattern as the original crop with nearly 75% mortality during the subsequent summer flood.

The 9 July 1989 prescribed burn was conducted over shallow standing water. Very few seedlings germinated initially, probably due to the standing water. The seed rain may have also been lower on this compartment because the burn was not as intense as the March burn and the seed trees were not fully scorched. Water levels rose between weeks 3 and 5 and the compartment remained flooded until week 17 (Figure 4). When the soil was again exposed, a mean = 18 seedlings/m² remained, but there was a second pulse of germination that raised the mean to 126 seedlings/m². Ninety-six percent of these died during the ensuing dry season. Those that remained were able to survive the second season of flooding, but all were killed when the compartment was reburned on 17 March 1991.

As with the compartment initially burned in March, the second burn in the July compartment stimulated release of seed that had been produced since the first burn as well as seed that had not been released by the initial low-intensity burn. Due to dry conditions, seedlings resulting from seed release stimulated by the reburn did not appear until 10 weeks after the fire. The mean = 160 seedlings/m², 50% of which died when the site was flooded for 13 weeks.

Moist soil at the time of burning simulated germination within 1 week after the January 1990 burn (Figure 5); by week 4 there was a mean = 2,137 seedlings/m², by far the highest density of seedlings recorded. During the 20-week dry season, the mean was reduced to 30 seedlings/m², but all of these were large enough to survive their first season of flooding and their second drought. This compartment was not subjected to a second burn.

The prescribed burns at the Monument Lake site killed >90% of the individuals 5–20 cm tall (Figure

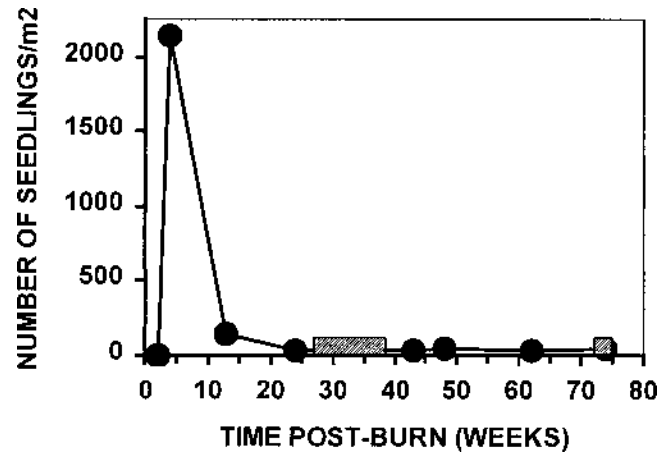


Fig. 5. Seedling establishment and survival following 17 January 1990 prescribed burn at Monument Lake site. Horizontal bars represent periods with standing water.

6). Mortality decreased with increasing size of plants. Among the burns, results were considerably more variable for larger size classes. The January burn was generally the least effective in killing young melaleuca. The March burn was most effective in killing plants ≤100 cm tall. Mortality was 99% of the individuals ≤50 cm tall and 92% of those ≤100 cm tall. The March burn was ineffective, however, in killing saplings >200 cm tall. On the other hand, the July burn was the most effective in killing the larger 2 size classes. The mortality observed in the control compartment was probably higher than normal due to the freezes experienced during the course of the study.

Figure 7 combines the mortality for all the burns, broken down into 20 size classes, each containing 35–99 individuals. All seedlings ≤10 cm tall died during the burns. These results suggest that burns can be expected to kill 90% of melaleuca up to 20 cm tall and about 50% of melaleuca up to 50 cm tall at similar sites.

The results of the shadehouse study revealed that

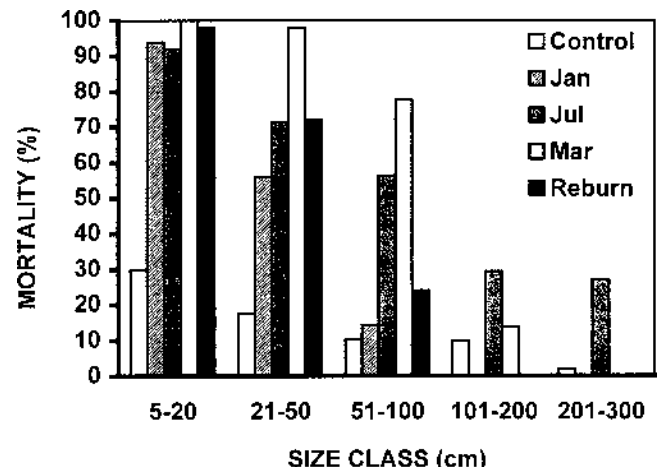


Fig. 6. Mortality of melaleuca seedlings and saplings within 5 height classes on an unburned compartment (control), 3 burned compartments, and a reburned compartment at the Monument Lake site.

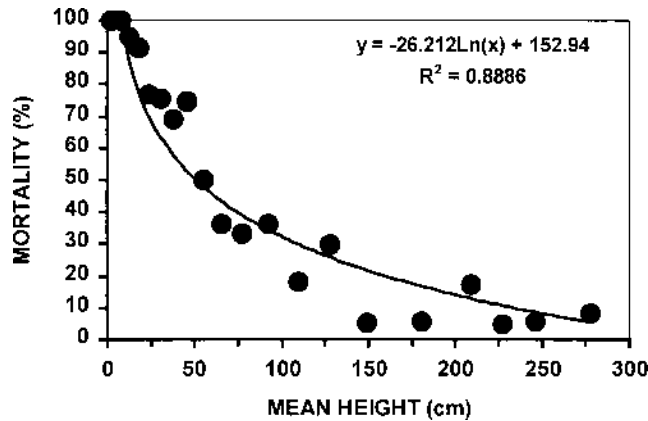


Fig. 7. Mortality of seedlings and saplings from all burns at Monument Lake site, grouped into 20 size classes.

no seedlings ≤ 3 months old survived top-killing (Figure 8). There were large differences in growth rates of seedlings in the 2 different substrates. Seedlings growing in sandy pineland soil were approximately 20 cm tall by 6 months, whereas seedlings growing in potting soil averaged approximately 2.8 cm tall (Figure 8). More than 20% of the seedlings growing in the sand substrate survived topkilling at 6 months, while none of the much smaller seedlings in the potting soil survived. The ability to withstand fire is not simply a function of size because seedlings 15 cm tall in the sand substrate experienced 93% mortality, while seedlings of that size growing more slowly in potting soil exhibited 27% mortality. It is likely that the pattern shown by seedlings in the sand substrate is more similar to the situation in the field in the Big Cypress area than the pattern shown by those grown in potting soil.

DISCUSSION

The results corroborate field observations and previous studies (Myers 1983) and show that melaleuca germination is greater on sites that have recently burned versus similar sites where vegetation, litter, and periphyton are intact, and that burning does not necessarily ensure successful establishment of melaleuca. Anecdotal observations of a paucity of seedlings established after herbicide treatment appear to be real. This suggests that in many cases there may be very few seedlings established as a result of such treatments. Seedlings that do become established could readily be killed by follow-up prescribed burns.

When considering the possible ramifications of fire on melaleuca seed release and the potential for spread, it is important to consider stand structure and age structure of the trees. Mature and emergent melaleuca trees produce, store, and release tremendous amounts of seed after burning. Fires in even-aged "dog hair" stands may burn without releasing many seeds because of a limited pool of stored seed. In control efforts where complete stand eradication is not possible in the short term, it may be useful to target mature outliers as well as emergents in dense stands. In other words, remove the trees producing the most seed first. A wild-

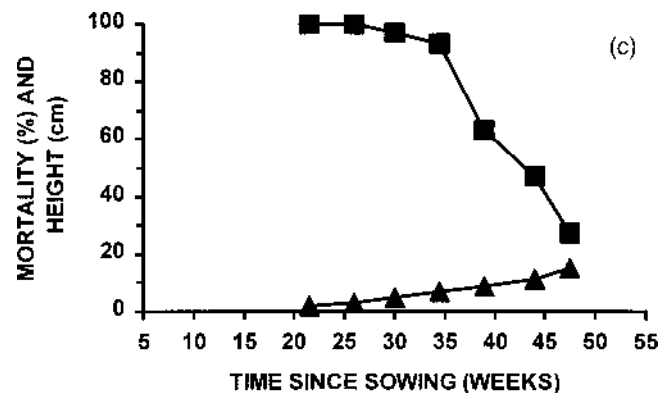
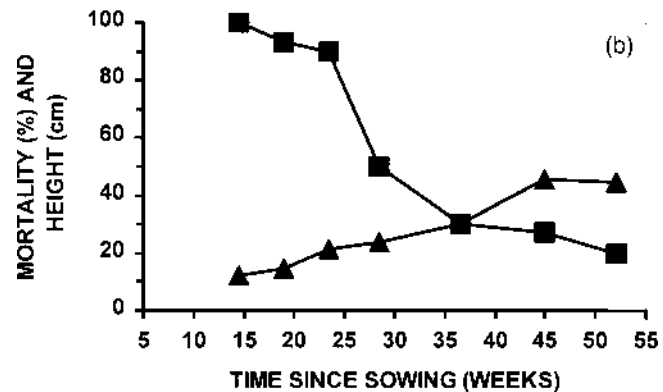
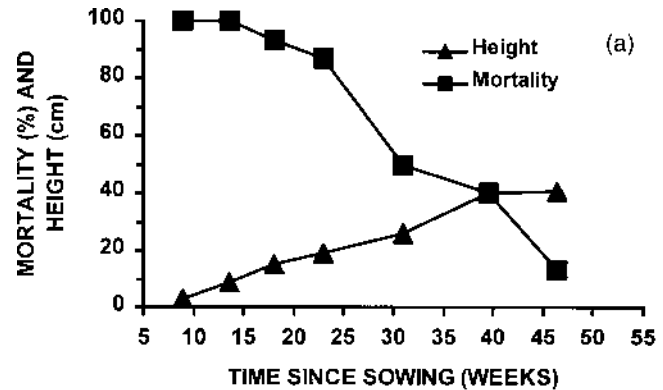


Fig. 8. Size and mortality of seedlings grown in shadehouse. (a) Sand substrate sown in July. (b) Sand substrate sown in August. (c) Potting soil substrate sown in August.

fire in the remaining stand may release relatively few seeds.

From the seed rain data collected during this study, it appears that $>95\%$ of the stored seed is released during the first 5 weeks post-burn. Even though the several thousand seeds/m² that continued to fall for several more weeks sounds like a large quantity, it may be insignificant in terms of potential establishment except under the most optimal conditions. Conversely, under these optimal conditions, a relatively small number of seedlings can cause big problems. Herbicide

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treatments that leave trees standing presumably result in even longer periods of seed release because the herbicides act more slowly than fire (Burkhead 1991).

Even though vast quantities of seeds are released, and large numbers of seeds may germinate, prolonged drought and periods of flooding can dramatically reduce the numbers of melaleuca seedlings established after a fire. Many of those that do survive can be killed by a second burn if it occurs within 2 years. Unfortunately, if seed trees are left on the site they will replenish their seed stores before the site has enough fuel to burn again.

The prescribed burns at Monument Lake point to several relationships between fire and melaleuca that should be considered in control efforts. First, fire can kill many, if not most, melaleuca seedlings. Second, some saplings can also be killed, but the likelihood of their surviving fire increases with size, and the vast majority of plants taller than 1 m survive. Third, muley prairie vegetation can be reburned at short enough return intervals to kill the majority of seedlings established after previous burns, but the short-interval reburn is ineffective in preventing a second seed release from pre-existing reproductive individuals. Fourth, fire may affect melaleuca mortality differently depending on individual fire behavior or season of burn. Melaleuca does not exhibit strong seasonal variation in its ability to recover after topkilling, unlike another South Florida exotic tree, *Schinus terebinthifolius*, or several native hardwoods (Snyder 1999). The hot March burn was very effective at killing plants <50 cm tall, while the mild January burn was less so. It is not clear why the very mild July burn at the Monument Lake site, which was not as successful in killing melaleuca <1 m tall as the more intense March burn, was the most detrimental to stems 1–3 m tall. One possibility may have to do with the extended period of flooding that immediately followed the July burn.

Big Cypress National Preserve was established as a unit of the National Park Service (NPS) during 1974. By that time, melaleuca introductions in the vicinity of Monroe Station, dating from the 1940s, had resulted in the largest and most rapidly expanding infestation in the preserve (Duever et al. 1979). The total area infested by melaleuca during 1979 was estimated at approximately 15,500 ha. Wildfires were suppressed and prescribed fire was avoided in areas with known melaleuca populations. Sporadic early efforts to control melaleuca in the preserve were ineffective and often resulted in more stems on site (Burkhead 1991). During 1984 the preserve began treating outlying stands with NPS crews. The treatment method at the time, basal "hack and squirt" herbicide application on trees, resulted in 77–94% mortality, depending on type of herbicide (Burkhead 1991). Saplings and seedlings were hand-pulled. Sites were revisited to re-treat trees that survived the herbicide treatment and to pull seedlings that were missed on initial treatment or that resulted from herbicide-stimulated seed release. The limited resources applied to the problem (about US \$60,000/year) did not appear to be making any headway because aerial surveys during 1992 showed about

48,000 ha of melaleuca infestations within the preserve (Pernas and Snyder 1999).

The availability of more effective herbicides, a shift in method of application, and the results of this research have led to the current treatment method: (1) plants <1 m tall are hand-pulled and stacked to prevent resprouting, (2) plants >1 m tall are cut with machete or chain saw and the stump surface is treated with herbicide (Arsenal or Rodeo, 25% diluted in water), and (3) the site is burned 2–12 months after treatment to reduce post-treatment seedling establishment (Pernas and Snyder 1999). Good coordination is important between the exotic plant management and fire management branches of the preserve so that fire can be introduced at the appropriate time to minimize seedling regeneration. Sites are monitored and re-treated on a 3-year cycle.

A major leap forward in melaleuca control occurred during 1994, when substantial funding became available to the NPS through a mitigation plan to satisfy permitting requirements for a joint Miami-Dade County and Florida Department of Corrections jail facility. More than US\$1,500,000 was provided to control melaleuca in a 8,700-ha area around Monroe Station. The NPS contracted the work with a private contractor and the initial treatment of the area, involving almost 4,000,000 stems, was completed during 1997 (Pernas and Snyder 1999). Currently there are no longer any sizeable stands of melaleuca remaining within the boundaries of Big Cypress National Preserve. With additional outside funding, the initial treatment of the entire preserve is anticipated by the end of 2001 (W.A. Snyder, National Park Service, personal communication).

The control of melaleuca is not yet finished because previously treated sites will have to be revisited to check for survivors and new seedlings for a few years and there are undoubtedly a few pockets of undetected trees. Furthermore, melaleuca infestations are widespread on both public and private lands outside the preserve. Vigilance will be needed to prevent a re-invasion. However, the success in ridding the preserve of what appeared to be an insurmountable problem demonstrates that melaleuca can be controlled in sizeable natural areas. The potential for biological control to play an important role in melaleuca control, while extolled, has not yet been realized (Laroche 1999). In the meantime, herbicide treatment of individual trees followed by prescribed fire seems to be the recipe for success.

MANAGEMENT RECOMMENDATIONS

The results of our research studies and field observations lead to the following recommendations for integrating prescribed fire into the control of melaleuca:

(1) On unburned sites cut down trees and treat stumps with herbicide. Felling the trees triggers seed release immediately and limits the wind-dispersal of seeds. Then treat the site with a follow-up prescribed

burn after the released seeds have had an opportunity to germinate, but before the seedlings have reached a size where many will survive the fire. In sites similar to those studied in Big Cypress, this would generally be 6–12 months after treatment. A similar approach is used in South Africa to control exotic pines (Bond and van Wilgen 1996), although there it is not necessary to treat the stumps with herbicide.

(2) In melaleuca-infested areas burned by wildfire, it is most important to treat mature trees with herbicide before they flower and set seed again. The site can then be prescription burned as soon as fuels are available, generally within 2–3 years. This should kill many of the seedlings resulting from the wildfire-caused seed release. Saplings that survive the fires would also have to be treated with herbicide.

These recommendations have been incorporated as part of the Melaleuca Management Plan by the Florida Exotic Pest Plant Council (Laroche 1999) and have helped the National Park Service accomplish its successful melaleuca control program at Big Cypress National Preserve (Pernas and Snyder 1999).

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